Remaining Useful Life Estimation (RULE) Methodology

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RULE Methodology

- **SPA has developed a Monte-Carlo simulation-based statistical technique for calculating the remaining fatigue life of dynamic components**
- **This technique shows excellent potential for increasing the fatigue life of critical components without decreasing their reliability**
- **The technique may also be used to remove over-stressed components earlier than anticipated to prevent premature failure**

RULE Development Program

- Developed to reduce the maintenance costs of helicopter flight critical components
- Developed during an OSD/US Army Phase I SBIR program that focused on analytical development and simulations
- Phase II program pending

Background Assumptions

- It is assumed that the components under consideration are primarily subject to static and alternating dynamic loads

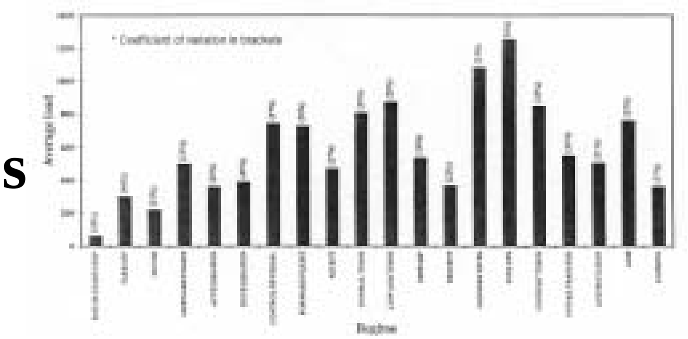
- The component's fatigue life follows the standard Miner's Law of Cumulative Damage for fatigue

- Real-time measurement of the components operating conditions (regimes, loads, or stresses) provides input into the RULE methodology

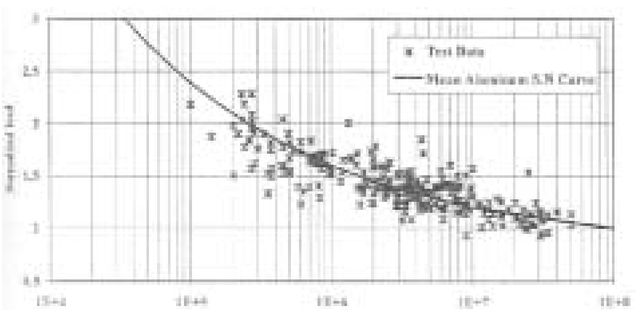
- The RULE methodology gives a amount of fatigue life that has been consumed by the component with a specified reliability

Current Rotorcraft Component Life Prediction Methodology

Assumed Usage Spectrum



Component Loads



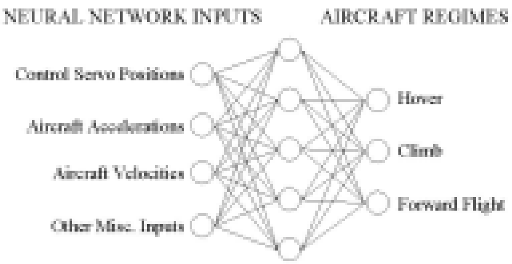
S-N Curve

Miner's Law of Cumulative Damage

Safe Life Limit

>99% Reliability

RULE Methodology
(using regime recognition)



Known Usage Spectrum

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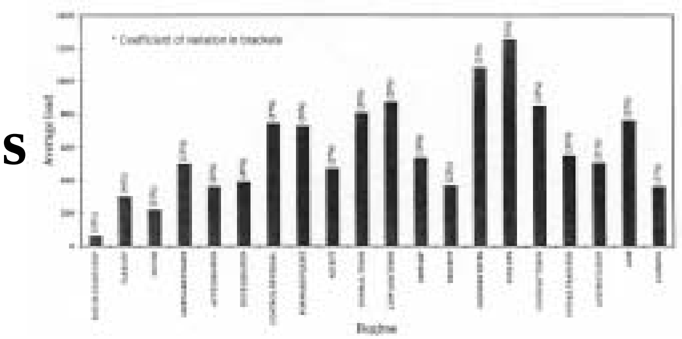
Component Loads



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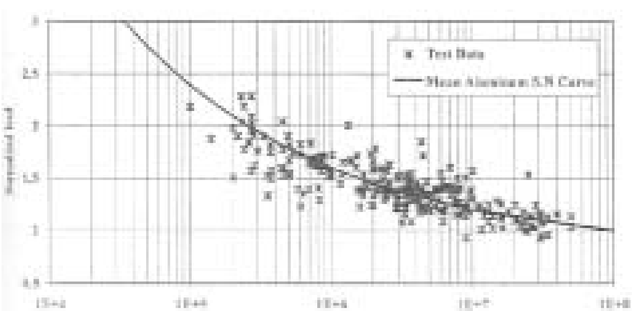

S-N Curve

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Miner’s Law of Cumulative Damage

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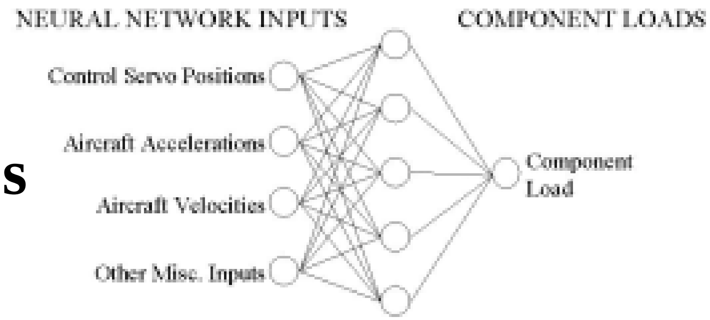
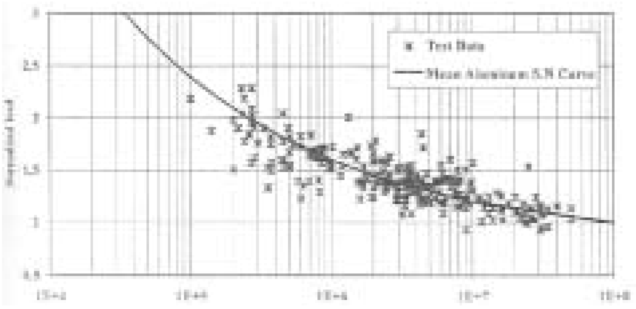
Safe Life Limit

>99% Reliability ???

RULE Methodology
(using predicted flight loads)



Known
Component Loads



S-N Curve

Miner's Law of Cumulative Damage

Safe Life Limit

>99% Reliability ???

Phase I SBIR Program Objectives

- Develop a neural network to perform flight regime recognition/flight loads prediction
- Optimize network parameters
  - Training/Validation data sets
  - Training methodology
  - Input parameters
- Investigate the effectiveness of the proposed statistical analysis technique for calculating remaining life

Phaes I SBIR Program Task 5: Statistical Reliability Analysis

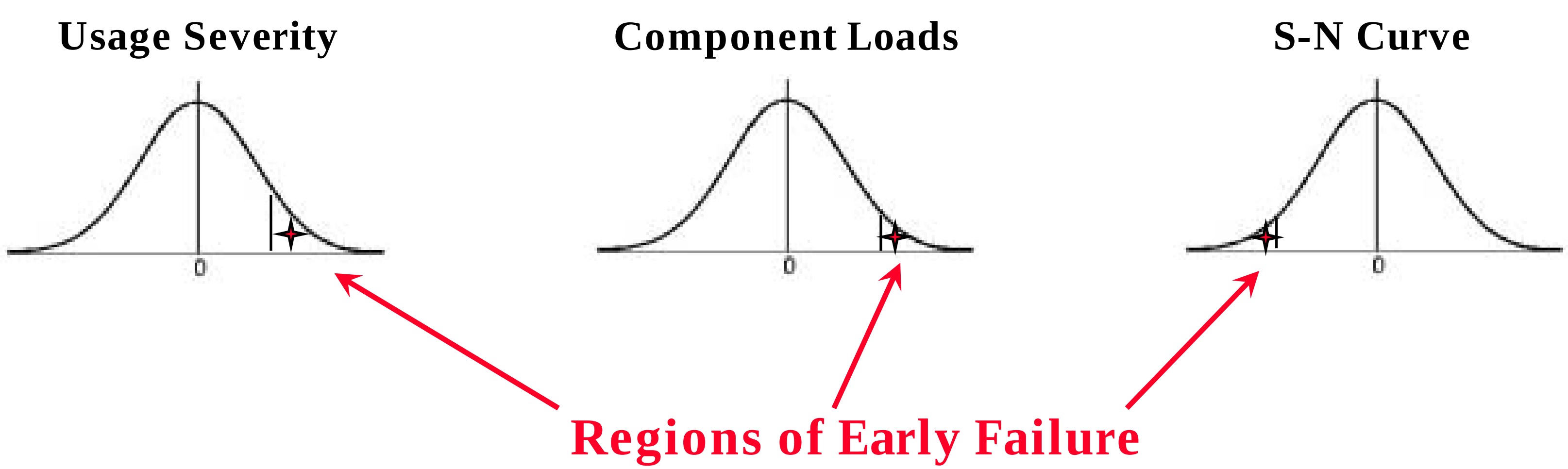
- **Preliminary investigation of a Monte Carlo based technique for predicting remaining useful life of individual components for a desired reliability will be completed using:**
  - **Small-scale models**
  - **Example problems**

Monte Carlo Simulation of Helicopter Component Life

- **Breakdown Component Life into Discrete Time Steps**
- **Choose Flight Regime, Component Loads, and S-N Curve for each Time Step**
- **Increment Life Used for Individual Time Step**
- **Determine Safe Life of the Component**
- **Locate Failure Scenarios**

Reliability Analysis

From the Monte-Carlo simulation



Average value within the failed regions

After performing usage monitoring (regime or flight loads) use these 'average' failed values to perform remaining life prediction with Miner's Law of Cumulative Damage

Helicopter Component Baseline Model

Regime Distribution and Loads

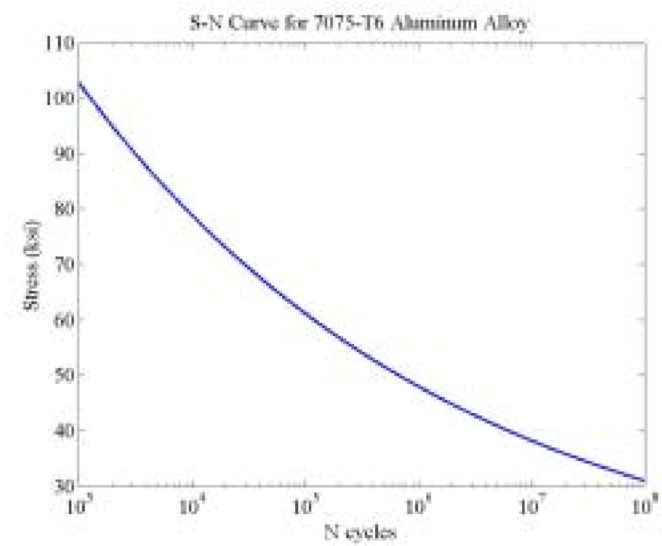
Regime	Percent Time	Average Load (lbs)	Standard Deviation (lbs)
Hover	20	100	10
Slow Level Flight	30	475	47.5
Fast Level Flight	30	650	65
Pullout	10	1500	150
Pushover	10	1200	120

S-N Curve

7075-T6 Aluminum from MIL-HNDBK-5

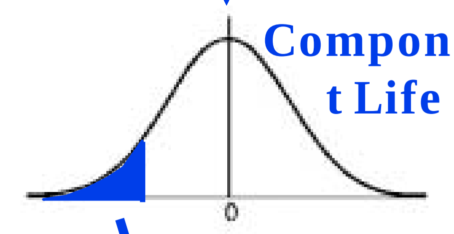
$$\log N = 18.21 - 7.73 \log(S - 10)$$

Endurance Limit set at 10 ksi



Simulation Technique

Monte Carlo Simulation



Componen
t Life

Extreme Usage Values

Fatigue Life Simulation

Actual Fatigue Life (using random values)

Predicted Fatigue Life (using extreme values)

Which one fails first?

Success/Fail ???

Regime Distribution Randomness

- **Early tests showed that the randomness of the regime distribution has the greatest effect on the component's useful life**
- **Extreme values for flight loads and S-N curve are therefore lower in the extreme cases (regime was severe but loads and S-N were normal)**
- **The technique did not work well when applied to blind simulations**

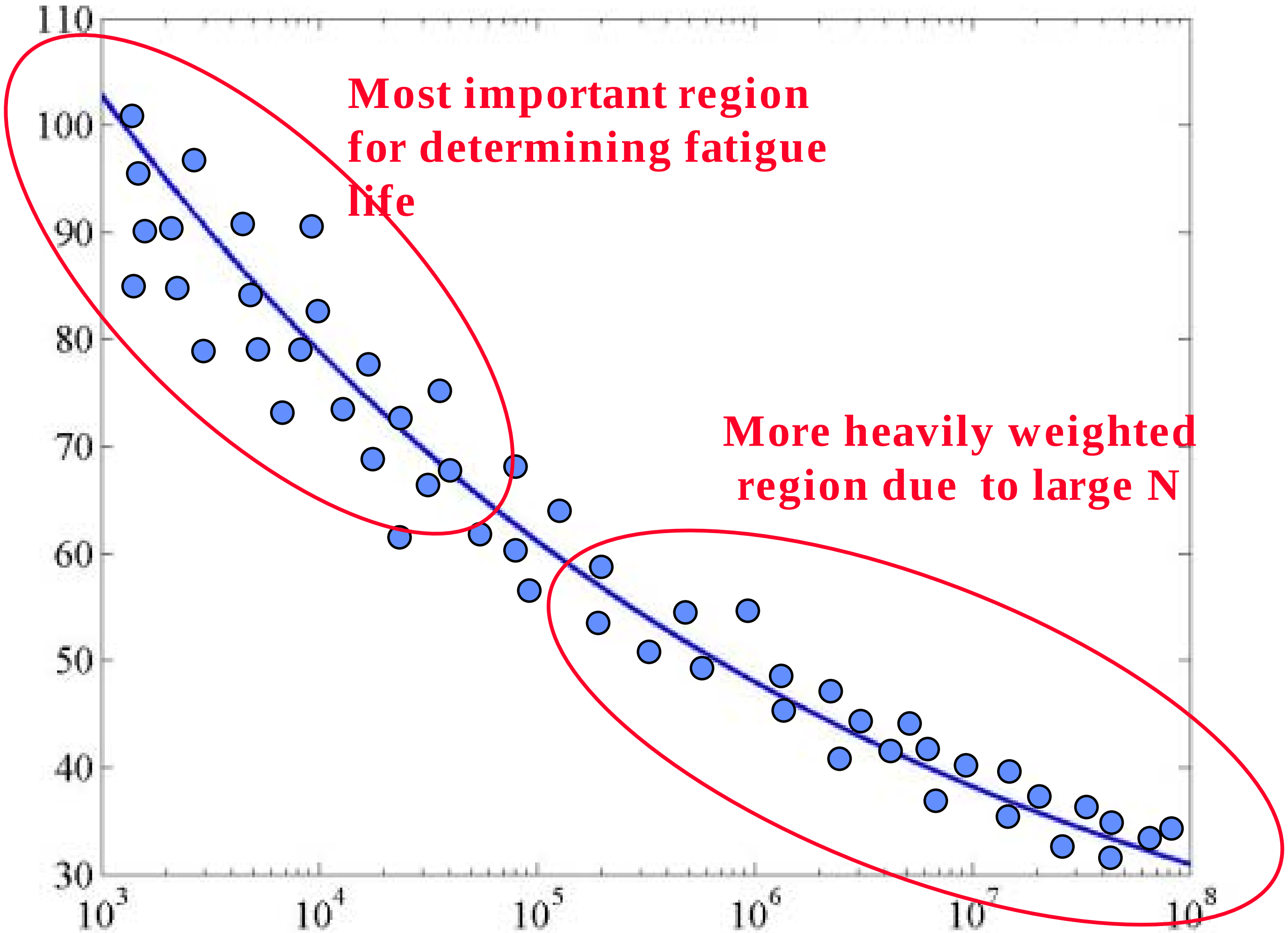
SOLUTION: FIX REGIME DISTRIBUTION DURING MONTE CARLO SIMULATION

Average Extreme Values

- Initial attempts involved simply averaging the extreme values
- Technique does not work well
- Flight load values were extreme but not extreme enough
- Method failed approximately 10% of the time

SOLUTION: MUST CONSIDER HOW THE RANDOM VARIABLE AFFECTS THE OVERALL RESULTS

Need for Inversion in Curve Fitting



Extreme ‘Inverse’ Algorithm

- **Fatigue life is a function of 1/N, not N**
- **From the Monte Carlo extreme loads, calculate stress and N (assuming no randomness)**
- **Invert N (because of Miner’s Law) and average, re-invert and back calculate extreme load**

Regime	**Average Load**	**Extreme Load - Averaging**	**Extreme Load - Inverse Technique**
Hover	100	100	100
Slow Level Flight	475	475.8	499.5
Fast Level Flight	650	651.1	675.8
Pullout	1500	1558.7	1783.1
Pushover	1200	1221.5	1236.0

Statistical Test Results

Various Distributions

	Percent Time in Regime							
Hover	20	25	30	35	0	25	35	50
Slow Level Flight	30	35	40	0	0	10	25	20
Fast Level Flight	30	30	20	45	80	50	30	20
Pullout	10	5	5	10	10	10	5	5
Pushover	10	5	5	10	10	5	5	5
% Failed	.36%	.38%	.43%	.35%	.38%	.35%	.41%	.29%

S-N Curve Randomness Only

- **Previous methodology is not valid if the neural network predicts component loads instead of flight regime**
- **Modify technique by ‘fixing’ the regime distribution and component loads in Monte Carlo simulation**
  - **All extreme cases come from extreme S-N curve points**
- **Use these points (inverted) with ‘known’ flight loads**
- **How do you curve fit to the assumed S-N curve? Mathematically extremely difficult and computationally intensive**
  - **Limit flight loads to have no randomness**

Flexibility of RULE

- **Although the Phase I SBIR focused on flight critical helicopter components, the methodology can be applied to other prognostics programs**
- **Alternative damage laws (other than Miner's Law of Cumulative Damage) can be easily incorporated into RULE**
- **Can be applied to any function with random variables**